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14. ABSTRACT

This symposium intersects materials research with the other sciences (physics, chemistry, biology and engineering) by bringing together some of the world's foremost scientists who share the fascination of the generation of motion on the nanoscale. The organizers anticipated that this symposium would enable discussions that help identify future directions for the development of molecular machines and inspire collaborative investigations uniquely present in this field.

Refer to attached summary and abstracts.

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PERFORMANCE REPORT FOR AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Award number: FA9550-08-1-0121
Conference Title: 2008 Materials Research Society Spring Meeting
Symposium FF: ***Molecular Motors, Nanomachines and Active Nanostructures***
Dates and Location: March 25 – March 26, 2008, Moscone West, San Francisco CA
Sponsoring Organization:
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Summary of activities:

Symposium FF: ***Molecular Motors, Nanomachines and Active Nanostructures*** brought together scientists from diverse fields working on the conversion of chemical energy into mechanical energy. Topics presented spanned the nano- (single molecule physics) to micro- (engineered and material systems) scales and included important issues for development of molecular motor devices: the control of actuation, elucidation of actuation mechanisms, determination of environmental interactions, and development of guidelines for engineering motors into devices. An exciting interplay between natural and synthetic motor systems recurred throughout the symposium. The symposium featured two days of oral presentations with four platform sessions, and a well-attended poster session.

Support for the symposium was generously provided by: the Chemistry and Life Science Directorate (Dr. Hugh DeLong) at the Air Force Office of Scientific Research (AFOSR); Cytoskeleton Inc. of Denver, CO, a supplier of a wide variety of products connected to the study of tubulin, actin, and motor proteins in easyto-use kits; Andor Technologies of Belfast, North Ireland, developers and manufacturers of high performance scientific digital cameras capable of single molecule detection; and the MRS who generously provides seed money to all of its symposia.

Session FF1 Synthetic Motors and Active Molecules

Symposium organizer Dr. Amar Flood led the first session. The first talk was held by one of the most accomplished researcher in the field, Dr. Ben Feringa from the University of Groningen. He described the recent advances in his group in creating synthetic motors from organic molecules and their integration into materials to create macroscopic effects. Contributed talks by Francisco Raymo and Dongwhan Lee were followed by the second invited talk by Miguel Garcia-Garibay from UCLA describing his experimental and theoretical advances in the the creation of “amphidynamic crystals”. Unit cells of these crystals contain “rotor” groups spinning around a “stator” group.

Four high-quality contributed talks by Shengrong Ye, James Guerrero (presenting for James M. Tour), Jovica Badjic and Sheng-Hsian Chiu were capped by one of the highlights of the conference, an extended contributed talk by Jeffrey Zink from UCLA. He presented on a device that acts at the nanoscale to control the delivery of chemicals from nanoporous silica. In the presentation, Zink outlined the approach of using the templated silica as a nanocontainer that employs molecular machines, in the form of rotaxanes, which can open and close the pore openings to release anything from dyes to drugs. New biocompatible rotaxane-based machines were attached around the rims of the pores to operate upon a change in pH when they enter cells. Zink showed how the entry could be visualized by the release of dyes suggesting the exciting opportunity to harness these devices for drug delivery. This potential and the related research conducted in a collaborative team have laid the foundation for the formation of a start-up company and we look forward to many more developments in this application area.

Session FF2 Biological Approaches in Nanoscale Motion

Symposium organizer Heiner Linke hosted the second session whose first half combined examples of engineered devices integrating myosin motors as well as cells. First, Alf Mansson from the University of Kalmar described in an invited talk how nanoscale surface patterning organize myosin motors and support directed gliding of actin filaments. Bryant Chase described how engineering advances in temperature control and flow regulation of myosin/actin gliding assays can generate novel insights into disease mechanisms. Yoshitake Akiyama presented his work on hybrid devices which integrate cultured cardiomyocyte tissues. The second invited speaker in this session, Dan Nicolau from the University of Liverpool, described his fascinating work on the ability of fungi to solve microfabricated mazes. Stefan Schwan presented a new experimental approach to nanoscale force measurements.

The emphasis after the coffee break was the theoretical understanding of biomotor systems. Unfortunately, Dean Astumian had to cancel his talk on short notice. George Oster (invited speaker), Stefan Klumpp and Ashutosh Agarwal discussed the kinetics and thermodynamics of the F0F1-ATPase, the dynamics of small motor arrays, and the dynamics of cargo loading onto molecular shuttles, respectively.

Session FF3 Poster Session

The poster session was very vibrant with 20 posters displayed by mostly junior researchers. Discussions between poster presenters and attendees of this symposium and the over forty over symposia lasted until 10 pm. The posters of Adrienne Greene (Sandia National Lab) and Kumar Parimal (Indiana University) were chosen as the two best posters of the session by a committee of three judges.

Session FF4 Motors and active Nanostructures from Proteins, DNA, and Cells

Symposium organizer Henry Hess chaired the first half of the session which centered on DNA systems. Three invited talks by Ned Seeman (New York University), Jonathan Bath (University of Oxford), and Niles Pierce (Caltech) drew the line from the first steps in this burgeoning field to the most recent advances, described e.g. in Nature magazine. The strong emphasis on topological consideration and algorithmic approaches in these talks provided an interesting counterpoint to the more mechanical perspective in the biomolecular motor subfield.

Hosted by honorary chair Kazuhiro Oiwa, one of the pioneers in the field, the second half of the session brought the state-of-the-art in the engineering of devices and nanostructures with biomolecular motors into focus. Stefan Diez presented his cutting edge microscopy techniques to image individual kinesin molecular motors as well as microtubules with nanometer accuracy. George Bachand discussed the formation dynamics of microtubule spools and presented detailed insights into their structural organization obtained by transmission electron microscopy. Taro Uyeda described the advantages of employing whole bacterial cells rather than extracted proteins. Utilizing gliding bacteria of the genus *Mycoplasma mobile*, his team succeeded in building a rotary motor at the microscale which was powered by these “microoxens”.

Session FF5 Fundamental Mechanism of Nanoscale Motion

Symposium organizer Heiner Linke directed this session, which approached the topic of nanoscale motion from the perspective of a physicist. Adam Cohen (invited speaker, Harvard) utilized electric fields to counteract the Brownian motion of nanoparticles and localize them with high precision. Christian van den Broeck (invited speaker, Hasselt University, Belgium) discussed the statistical thermodynamics of Brownian ratchet systems in a talk which at the same time focused at the fundamental aspects and was accessible to the majority of the audience. Keith Schwab (invited speaker, Cornell) presented experiments aimed at achieving the complete absence of motion – the vibrational ground state in microfabricated oscillators.

Contributed talks by Ersin Altintas and Jose Vicent discussed experiments and theory connected to Brownian ratchets before Robert Blick (U. of Wisconsin, Madison) gave the final presentation of the symposium. His recent work focused on the use of nanomechanical oscillators as switches.

SUMMARY

Symposium FF: ***Molecular Motors, Nanomachines and Active Nanostructures*** presented a wide-ranging overview of the state-of-the-art in the molecular motor field. Attendance was strong, with 50 to 100 scientists in the audience for almost all talks. The large fraction of invited talks resulted in a consistently high quality of presentations from the leaders in the field. Thematic organization of topically related talks enabled the direct comparison of related approaches, but somewhat reduced the cross-fertilization between fields. As a venue for this interdisciplinary symposium, the MRS meeting has substantial advantages: San Francisco is centrally located, the Materials Research Society represents somewhat the smallest common denominator for chemists, physicists, biologists, and engineers, and the large number of parallel symposia draws in attendees who are more peripherally interested in molecular motors. The main disadvantage is that the accessibility of San Francisco enables the attendance of only select sessions.
As a consequence, the organizers (Flood, Hess, Linke, Turberfield) are currently debating the merit of a potential topical Gordon Research Conference.

A follow-up conference, either as a symposium at the MRS spring meeting or an independent Gordon Research, is planned for 2010.

The organizers of this symposium sincerely thank Dr. Hugh DeLong for his continued support!

Materials Research Society
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Home Meetings 2008 Spring Meeting Abstracts

Symposium FF: Molecular Motors, Nanomachines, and Active Nanostructures

SYMPOSIUM FF

FF: Molecular Motors, Nanomachines, and Active Nanostructures

MRS spring meeting 2008 San Francisco • CA March 24–28

March 25 - 26, 2008

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Symposium Proceedings Series.

* Invited paper

SESSION FF1: Synthetic Motors and Active Molecules
Chair: Amar Flood
Tuesday Morning, March 25, 2008
Room 3018 (Moscone West)

8:30 AM *FF1.1
In Control of Motion with Synthetic Molecular Motors. Ben L. Feringa, Chemistry, University of Groningen, Groningen, Netherlands.

Molecular motors are among the most challenging goals of nanoscience and will proof crucial to power future nanomachines.The design of synthetic molecular motors to achieve controlled translational and rotary motion is discussed. Progress in our program toward controlled motion on surfaces, the acceleration of rotary motors and molecular motors at work will be described.

9:00 AM FF1.2
Fast and Stable Photochromic Oxazines. Francisco M Raymo, Chemistry, University of Miami, Coral Gables, Florida.

In search of strategies to improve the switching speeds and fatigue resistances of spiropyrans, we have designed and synthesized a new family of photochromic compounds based on the photoinduced opening and thermal closing of [1,3]oxazine rings. Specifically, the laser excitation of these molecules at 355 nm cleaves a [C-O] bond with the concomitant opening of a [1,3]oxazine ring in less than 6 ns and with quantum yields ranging form 0.03 to 0.28 in acetonitrile at ambient temperature. This process generates a 4-nitrophenolate chromophore with the concomitant appearance of a ground-state absorption at 440 nm. The photogenerated isomers revert to the original species with first-order kinetics and lifetimes ranging from 25 to 140 ns. Thus, a full switching cycle can be completed on a nanosecond timescales with these photochromic switches. Furthermore, these compounds tolerate thousands of switching cycles with no sign of decomposition even in the presence of molecular oxygen. In addition, these molecules can be trapped within rigid polymer matrices and operated under these conditions with microsecond switching speeds.

9:15 AM FF1.3
Shape-Adaptive Chemical Architectures: Cooperative Mechanical Coupling Schemes for Assembly, Transport, and Sensing. Dongwhan Lee, Chemistry, Indiana University, Bloomington, Indiana.

With an increasing demand to reduce the size and dimensions of electronic and mechanical devices, significant research efforts have recently been made in synthetic chemistry front to construct higher-order assemblies from molecular building blocks. Critical to the success of this bottom-up approach is the availability of functional components that can relay signals over a long distance with high fidelity. Many naturally occurring machinery can amplify local structural distortions and transduce them to chemical signals at remotely located sites. Unlike electronic coupling, such mechanical coupling in general is less restricted by the distance requirements between the two communicating parts. Drawing inspirations from naturally occurring constructs, we have designed and synthesized a new class of C_3-symmetric aromatic-rich compounds displaying correlated molecular motions. These structurally pre-organized but conformationally flexible molecules have proven to be versatile functional components in molecular devices and materials for transport, switching, and sensing. Extreme modularity in our synthetic design, along with novel structural and electronic properties associated with the tris(N-salicylideneamine) functionality, has allowed us to demonstrate the feasibility of (a) uptake and release of small molecule guests by shape-adaptive organic crystalline materials, (b) self-assembly of discotic molecules displaying enhanced emission properties upon aggregation, (c) fluorescence sensing and switching by mechanical control of excited-state geometry, (d) FRET as a viable mechanism for sensory signal amplification and allosteric switching, and (e) cooperative structural folding for predetermined helicity and its translation to supramolecular chirality of nanofibril structures. In this presentation will be discussed the advent, current progress, proposed evolution, and potential applications of the shape-adaptive molecules developed in my laboratory.

9:30 AM *FF1.4
Amphidynamic Materials and Molecular Machines: Approaching Barrierless Motion in Crystalline Solids. Miguel A Garcia-Garibay, Chemistry and Biochemistry, UCLA, Los Angeles, California.

Growing interest in artificial molecular machinery has recently led to the exploration and development of amphidynamic crystals, a new class of functional materials with physical properties that may be modified by controlling their internal motion in the solid state. Our contributions in this area have covered molecules with shapes and function analogous to those of macroscopic gyroscopes. They consist of an intrinsically barrierless dialkynyl rotator that acts as the dynamic component, such as axially substituted 1,4-dialkynyl phenylenes, and two triarylmethyl (trityl) or triptycyl groups that act as the stator. In our quest to design crystals with internal dynamics that approach gas phase frequencies and barriers, we have prepared and analyzed several molecular gyroscopes with novel high-symmetry rotators, including structures with bicyclo[2.2.2]octanes, carboranes, cubanes and diamantanes, as well as structures with triply bridged and “exploded” stators.

10:30 AM FF1.5
Autonomous Motion: Tracking the Behavior of Catalytically Powered Janus Particles. Shengrong Ye, Hua Ke, Mikala Shremshock, Kenneth Showalter and R. Lloyd Carroll; West Virginia University, Morgantown, West Virginia.

Devices and systems based on the autonomous motion of nanoscale objects in a fluid environment have tremendous potential but are still in the very early stages of development. The conversion of stored chemical energy into mechanical motion via chemical catalysis is a particularly appealing approach. Catalytic reduction of a soluble fuel (such as hydrogen peroxide) has been demonstrated to induce motion of micro- and nanoscale objects across several length scales. In all cases, the motile structures were asymmetric in structure, leading to differential activity on one side compared to the other. However, the mechanism of the induced motion remains unresolved. One simple strategy to prepare a broken symmetry system that will undergo self-propelled movement is through the use of “Janus” particles. In this work, we have developed a chemically-powered asymmetric system of catalytic Janus particles derived from silica microspheres half-coated with metals. When placed in a solution of a chemical fuel, these particles undergo driven motion, which can be observed by tracking the motion of the particles with respect to time. Analyses of the dynamics of the system clearly differentiate the motion of the particles from Brownian motion. In addition, the particles should undergo rotational diffusion. To image the rotational orientation, the exposed silica regions of the Janus particle were functionalized with CdSe quantum dots. The three-dimensional orientation of the particle may be determined from analysis of the fluorescence images of the beads. Through variation of the experimental conditions and observations of differences in rotational and lateral diffusion, the mechanism of motion may be addressed.

10:45 AM FF1.6
NanoCars. James M Tour, Chemistry Department, Rice University, Houston, Texas.

Nanovehicles are a new class of molecular machines consisting of a molecular scale chassis, axles, and wheels that can roll across solid surfaces with structurally defined directions. In this talk, our recent progress on the nanovehicle project is presented including the design, synthesis, and testing of a series of nanocars, nanotrucks, and motorized nanocars. Imaging using STM and fluorescence microscopy will be discussed.

11:00 AM FF1.7
Gated Molecular Baskets. Jovica Badjic, Ohio State University, Columbus, Ohio.

It is a challenge to fundamentally address the relationship between structure and function in complex chemical environments. Our approach consists of investigating the mechanism of operation of folded molecules that are designed to perform useful functions. First, we have studied the working mechanisms of basket-like hosts capable to fold and thus incarcerate a guest. The folding process is mediated by intramolecular hydrogen bonding or metal-to-ligand coordination of the heterocyclic "flaps" appended to the basket rim. The incarceration of a guest is dictated by (a) its coordination to the metal cation, or (b) rapid opening and closing of the hydrogen bonding 'flaps". In this way, the guest exchange is restricted by the baskets' conformational behavior, which allows exploring the relationship between the molecular exchange kinetics and chemical reactions occurring in the confined space. Second, we have been developing molecular machines, "allosteric molecular resonators", to investigate the controlled and synchronized motions of distant molecular parts in artificial systems. The constrictive binding, allostery and cooperativity have been altogether put at work for obtaining assemblies capable to perform complex operations.

11:15 AM FF1.8
Using Anions to Operate the Translational Isomerism of a [2]Rotaxane. Sheng-Hsien Chiu, Chemistry, National Taiwan University, Taipei, Taiwan.

Although using cations to switch interlocked machine-like systems between different states is quite common, reports of anion-mediated interlocked switches are rare. To the best of our knowledge, only a few examples of anion-controlled translational isomerism in interlocked molecular switches have been described previously: (1) generating a phenoxide anion on a rotaxane thread to attract Leigh's macrocycle and (2) exchanging the counteranions of ammonium or pyridinium ions to affect their interactions with complementary crown ether or naphthalene recognition motifs. In this meeting, we report: (1) a molecular [2]rotaxane comprising a molecular cage and a dumbbell-shaped component, the latter incorporating two pyridinium and two dialkylammonium centers, in which translational isomerism can be performed reversibly through an in situ anion exchange process, i.e., sequential addition of Bu4NCl/AgPF6 reagent pairs and (2) a new ditopic macrocyclic host that is capable of recognizing a diphenylurea-derived thread in a [2]pseudorotaxane-like fashion in solution and the controllable translational isomerism of its corresponding neutral [2]rotaxane was achieved through the addition and removal of acetate anions.

11:30 AM *FF1.9
Nanoparticles and Molecular Machines for Drug Delivery and On-Command Release. Jeffrey I Zink, Chemistry and Biochemistry, UCLA, Los Angeles, California.

Mesostructured silica thin films and particles prepared by surfactant-templated sol-gel techniques are highly versatile substrates for the formation of functional materials. The ability to deliberately place molecules possessing desired activities in specific spatially separated regions of the nanostructure is an important feature of these materials. Such placement utilizes strategies that exploit the physical and chemical differences between the silica framework and the templated pores, and enables molecular machines to be synthesized. Molecules that undergo large amplitude motion, when attached to the silica, can function as impellers and nanovalves when activated by light, electrical (redox) and chemical (pH, competitive binding) energy. Derivatized azobenzene molecules, attached to pore walls by using one of the placement strategies, function as impellers that can move other molecules through the pores. Rotaxanes and pseudorotaxanes, placed at pore entrances, function as gatekeepers or valves that can trap and release molecules from the pores when stimulated. Examples of these machines and their operation are discussed. Nanoparticles of mesostructured silica containing impellers or valve-controlled pores serve as controllable drug delivery vehicles. Uptake of these functional particles by living cells and release of drug molecules upon external command are described.

SESSION FF2: Biological Approaches in Nanoscale Motion
Chairs: Henry Hess and Heiner Linke
Tuesday Afternoon, March 25, 2008
Room 3018 (Moscone West)

1:30 PM *FF2.1
Molecular Motors in Nanoscale Surface Characterization and Organization of Biomolecules on a Chip. Alf Mansson[1], Petr Vikhorev[1], Nuria Albet-Torres[1], Martina Balaz[1], Natalia Vikhoreva[1], Mark Sundberg[1], Richard Bunk[2], Kenneth Liljesson[1], Leif Nilsson[4], Babak Heidari[3], Sven Tagerud[1], Ian A Nicholls[1], Par Omling[2] and Lars Montelius[2]; [1]University of Kalmar, Kalmar, Sweden; [2]Lund University, Lund, Sweden; [3]Obducat AB, Malmö, Sweden; [4]LHV Mätfakta, Kalmar, Sweden.

In several recent studies nano- and microstructured surfaces have been used to achieve guidance of molecular motor based transport with the objective to develop lab-on-a-chip devices. From these studies it is clear that 1. the motor function is strongly dependent on the underlying surface chemistry, 2. the motor driven transport of e.g. actin filaments is apparently random in the absence of chemical and topographic guiding and 3. the motor propelled filaments act as less than 10 nm wide scaffolds with regularly spaced, specific binding sites (e.g. lysine residues), for other biomolecules. Here, these properties are analyzed in greater detail in relation to their possible exploitation in characterization and organization of surfaces. Recently, we observed good correlation between water contact angles (from 10 to 80 degrees) of pure and silanized glass and SiO2-surfaces and the capability of adsorbed heavy meromyosin (HMM) motor fragments to propel actin filaments. Studies using total internal reflection fluorescence spectroscopy, quartz crystal microbalance and ATPase assays, with a fluorescent ATP analogue, attribute the correlation to different HMM configurations on surfaces with differing contact angles and charge. A detailed model for the HMM adsorption will be presented together with arguments that HMM adsorption, HMM catalytic activity and HMM propelled actin filament sliding may be exploited for highly parallel, far-field light-microscopy based characterization of surface chemistry on the nanoscale. The other main facet of this work is motor-driven organization of surfaces with particular emphasis on time-varying 2-dimensional gradients of biomolecules, with potential usefulness in sensing applications and cell biological studies. In this process, a large ensemble of HMM propelled actin filaments, are spreading on a surface according to a diffusion equation with an apparent diffusion coefficient (D) proportional to the sliding velocity and the persistence length (P) of the filament path. The possible relationship to the persistence length of the actin filament itself will be considered. Interestingly, the parameter D can be directly related to an energy term and drag forces in analogy with the Einstein equation. Thus, $D = \Delta G/\gamma$ where ΔG is the free energy of ATP hydrolysis required to propel the actin filament a distance determined by P. The effective drag coefficient, γ, on the other hand, is proportional to the average on-time of an actomyosin interaction. Gradients of approximately Gaussian shape of HMM-propelled actin filaments and actin-attached biomolecules will be described for non-patterned surfaces. Moreover, as will be exemplified, micrometer scale gradients of arbitrary shapes may be produced by motor driven “diffusion” of actin filaments on suitably micropatterned surfaces. The characteristic features of these types of gradients will be discussed.

2:00 PM FF2.2

Molecular Motor-Based Assays for Altered Nanomechanical Function of Ca^{2+}-Regulatory Proteins in Cardiomyopathies. P. Bryant Chase[1,2,5], Nicolas M. Brunet[2,1,6], Goran Mihajlovic[4,3,7], Peng Xiong[4,3] and Stephan von Molnar[4,3]; [1]Biological Science, Florida State University, Tallahassee, Florida; [2]Molecular Biophysics, Florida State University, Tallahassee, Florida; [3]Physics, Florida State University, Tallahassee, Florida; [4]Materials Research and Technology (MARTECH), Florida State University, Tallahassee, Florida; [5]Chemical and Biomedical Engineering, Florida State University, Tallahassee, Florida; [6]Physiology & Biophysics, University of Washington, Seattle, Washington; [7]Materials Science Division, Argonne National Laboratory, Argonne, Illinois.

A thermo-electrical control system for biomolecular motors and their partner filaments (Mihajlović et al., 2004, Appl. Phys. Lett.) can also be used to study molecular mechanisms in cardiovascular diseases. We have used this device to evaluate the temperature-dependence of actin filament sliding powered by myosin in the absence (unregulated) or presence (regulated) of recombinant, bacterially-expressed human cardiac regulatory proteins tropomyosin (α-Tm) and troponin (Tn) under controlled conditions of Ca^{2+} and ATP. By fluorescence video-microscopy, we have demonstrated: faster filament sliding for regulated thin filaments at saturating Ca^{2+} when compared with unregulated actin over a wide temperature range (10 - 54°C); similar activation energies (E_a) for regulated and unregulated actin above physiological temperature; and higher E_a for regulated actin below physiological temperature, while unregulated actin exhibits constant E_a over the entire temperature range studied. Above 54°C, speed of regulated actin at saturating Ca^{2+} anomalously decreased toward that of unregulated actin. In the absence of Ca^{2+}, filament sliding was observed at temperatures greater than ~ 45°C; this temperature-dependent loss of regulation at pCa 9 was fully reversible. Together, these results with WT Tn and α-Tm suggest that elevation of temperature leads to loss of function of α-Tm and/or Tn. When wild type (WT) α-Tm was replaced by familial hypertrophic cardiomyopathy (FHC) mutant E180G, sliding speed (pCa 5) was similar to WT in the range 25 - 39°C, but was slower than WT as temperature was raised to 50°C suggesting that this mutation destabilizes the structure and thus function of Tm. Temperature-motility profiles of several FHC mutants of Tn (pCa 5) exhibited differences in the temperature at which E_a changes, suggesting that these Tn mutations alter different aspects of Ca^{2+}-regulatory protein function than the α-Tm mutation. Assays using the thermo-electric controller thus provide functional correlates of structural stability in multi-protein assemblies—structural data that challenging to obtain in solution—and thereby allows us to test for altered stability of clinically relevant mutations of cardiac myofilament proteins. Support: NIH/NHLBI HL63974, NSF ECS-0210332 and AHA FL/PR Affiliate 0315097B

2:15 PM FF2.3

Culture of Insect Heart Muscle Tissues and its Applicability to Bio-Actuators. Yoshitake Akiyama[1], Yuji Furukawa[1], Keisuke Morishima[1] and Kikuo Iwabuchi[2]; [1]Department of Mechanical Systems Engineering, Tokyo University of Agriculture and Technology, Tokyo, Japan; [2]Department of Applied Biological Science, Tokyo University of Agriculture and Technology, Tokyo, Japan.

Fundamentals of bioactuators using mammalian heart muscle cells were reported so far, such as pillar actuator, micro pump, self-assembled micro device, muscular thin film, etc. However, they are not yet realized in practice because the required culture conditions of pH and temperature for mammal cells are difficult to keep, furthermore, they can only work under 5% CO2-atmosphere and culture medium has to be replaced every few days. Regarding insect cells, on the other hand, they seem to be robust over a wide range of culture conditions as they are poikilothermic, and are expected as a new candidate for a bioactuator element which can overtake defects of mammal cells. Unfortunately, there is no report to have cultured insect heart muscle cells and apply them to a bioactuator element. In the present paper, a moth is chosen among many insects as it is known very robust, and its heart muscle tissues are excised and cultured as a bulk of cells because the culture of cell itself is quite difficult. A moth larva has a long and thin tubal heart called “dorsal vessel DV.” Lepidoptera larvae, Ctenoplusia agnata were used in this study. Resulting from culture examinations, the suitable culture conditions for keeping DVs contracting were determined as TC-100 medium with 20% FBS and 5% hemolymph, Cell-Tak Coating, 25 degrees C. The micropillars, 1000μm in height and 100μm in diameter were fabricated by forming poly (dimethylsiloxane) PDMS in a PTFE mold with drilled holes. The micro pillars were coated with Cell-Tak after oxygen plasma treatment. The excised DVs were plated on the pretreated micropillars after mechanically mincing, which were cultured under the conditions described above but without medium replacement. On the 2nd day, the micropillar began to move autonomously by cyclic shrinking of muscle tissues and could continue for more than 60 days. The frequencies of motion seem to depend on the inherent characteristic of tissue and were about 0.2 or 0.25 Hz in the present study. As a result of image analysis on the 37th day, the maximum displacement of gravity center of the micropillar’s top was 19 μm. The driving force estimated by that is about 4.6 μN which is larger than 3.4 μN by cardiomyocytes reported by Y. Tanaka et al. Furthermore, the pillars could be actuated when electric stimulus is given to the cultivated tissue, that suggests a possibility to control pillar’s motion from outside too. As above mentioned, the moth heart tissue was cultured rather easier than that of a mouse, and was connected to micropillars. This fundamental bio-mechanical system could work either autonomously or heteronomously, and its durability was more than 60 days even without medium replacement. Taking these merit into account, the cultured insect cell tissue seems to possess a high potential as a bioactuator element, hence much possibility to be applied to bio-MEMS in near future.

2:30 PM *FF2.4

Molecular Motors-driven Fabrication of Natural Microfluidics Networks: The Case for Fungal Intelligence. Dan V Nicolau, Electrical Engineering & Electronics, University of Liverpool, Liverpool, United Kingdom.

All multi-cellular living organisms are very large and very complex microfluidics systems, which -in contrast with the artificial microfluidics devices- are ‘fabricated’ ‘inside-out’, rather than using top-down processes. As the complexity of the human-made microfluidics devices (e.g. number of valves/volume) increase yearly at a rate that surpasses the Moore’s Law of semiconductor devices, lessons from the nature regarding the optimality of molecular motors-driven processes of building of, and transport through natural microfluidics devices are very timely. Fungi, which are one of the most microfluidics device-like organisms, have developed very efficient space-searching strategies, as suggested by their success in colonizing habitats comprising micro-confined networks (e.g., soil, wood, leaf litter, plant and animal tissues). The growth of these natural, fungal microfluidics networks is the result of a complex tug-of-war process comprising both feed-forward modules, in particular the programme embedded in the species’ DNA, and feed-back processes, in particular the response to external environmental conditions. In a sense, the natural microfluidics systems solve a perennial mathematical problem: for an environment of limited resources (level of nutrients, geometrical confinement, competition from other species, etc.), finite growth rate and penalties applied to non-optimal behaviour - what is the best strategy that will maximise growth and survival of either the individual or -in extreme cases- the species? In some instances, e.g., natural micro-labyrinths, microorganisms do solve problems that are both complicated and in a graph format. Importantly, the most critical “computation resource” for space searching (and growth) is -arguably- the cytoskeleton. The actin filaments and microtubules constitute the trajectory of the space search, as well as the tracks used by molecular motors to build the fungal microfluidics “device”. It has been found that the molecular motors- and cytoskeleton-driven fungal processes posses an optimality which is tailored to the geometrical characteristics of the native environment. While the collision-induced branching of cytoskeleton is a remarkable method to increase the efficiency of space searching, the most striking space searching subroutine is the preservation of the directionality of the formation of the cytoskeleton over long distances. We present the space searching algorithms used by two very different fungal species, i.e. Pycnoporus cinnabarinus and Neurospora crassa, and discuss the respective differences and similarities in the context of optimality of space searching performed by cytoskeleton formation.

3:30 PM *FF2.5
How the World’s Smallest Rotary Motor Works. George Oster, George Oster, University of California, Berkeley, California.

ATP synthase (also called FoF1 ATPase) is the universal enzyme that manufactures ATP from ADP and phosphate using the energy derived from a transmembrane protonmotive gradient. It can also reverse itself and hydrolyze ATP to pump protons against an electrochemical gradient. This protein consists of two rotary motors connected to a common shaft, and rotating in the opposite direction. The F1 motor generates a mechanical torque using the hydrolysis energy of ATP. The Fo motor generates a rotary torque in the opposite direction using the energy stored in a transmembrane electrochemical gradient. Thus ATP synthase comprises what must be the world's smallest rotary engine. Each motor can be reversed: The Fo motor can drive the F1 motor in reverse to synthesize ATP, and the F1 motor can drive the Fo motor in reverse to pump protons. Thus ATP synthase exhibits two of the major energy transduction pathways employed by the cell to convert chemical energy into mechanical force. I will present a model for this molecular machine that accounts for all of the experimentally measured mechanochemical behavior.

4:00 PM FF2.6
Measurement of Forces Generated by Chemomechanical Protein Aggregates using Polymer BioMEMS. Stefan Schwan[1], Nicholas Ferrell[2], Andreas Cismak[1], Uwe Spohn[1], Andreas Heilmann[1] and Derek Hansford[2]; [1]Biological Materials and Interfaces, Fraunhofer Institut Werkstoffmechanik, Halle (Saale), Germany; [2]Department of Biomedical Engineering, Ohio State University, Columbus, Ohio.

Chemomechanical protein aggregates in plants, e.g. the p-protein bodies in phloem cells of legumes (forisomes), transform the chemical free enthalpy of their reaction with calcium ions into mechanical energy [1]. The thermodynamic cycle process can be closed by the extraction of these calcium ions with ethylenediamine-tetraacetic acid. Scanning electron microscopy (SEM) investi¬gations have demonstrated that the spindle-shaped bodies with sizes between 25 and 40 μm consist of fiber bundle units which change their length and diameter during the reversible switching. Due to the reaction with Ca(II), Sr(II) or Ba(II) ions, the protein aggregates contract by 10 to 40% of their original length and increase their cross sectional area. The stability of the energy conversion depends on the dissolved oxygen and can be considerably improved by working under anaerobic conditions. In addition to using the bending of glass fibers, micromechanical forces generated by the switching of forisomes in aqueous solutions were measured by monitoring the bending of thin polymer beams. The forisomes were fixed by chemisorption to four orthogonal beams of a MEMS microsystem designed and manufactured using the process of sacrificial layer micromolding [2]. Each beam has a length of 250 μm, thickness of 2.3 μm, and 5 μm width. Considering the elastic modulus of the beam and the beam geometry, the displacement of the beam end observed with an inverted microscope can be correlated with the measured static force. The set-up allows parallel measurement of static tensile force and compressive force between 10 and 500 nN. With this technique, the forces generated by different forisomesin response to changes in ion concentration and the pH value were measured in vitro. By reacting with 10 mM of Ca(II) different forisomes generate forces between 20 and 100 nN. The mechanical work related to the protein mass is approximately ten times higher than that of the main muscle of a bird wing. The relatively strong forces open up a new way to construct bioactuators for microfluidic systems. [1] Schwan, S.; Fritzsche, M.; Cismak, A.; Heilmann, A. Spohn, U. In vitro investigation of the geometric contraction behavior of chemo-mechanical P—protein aggregates (forisomes) Biophysical Chemistry, 2007, 125, 444-452 [2] Ferrell, N.; Woodard, J.; Hansford, D. Fabrication of polymer microstructures for MEMS: sascrificial layer micromolding and patterned substrate micromolding, Biomedical Microdevices 2007, 9 (in press).

4:15 PM *FF2.7
Quantifying the Transport of Cargoes Pulled by Several Molecular Motors. Stefan Klumpp[1], Janina Beeg[2], Melanie J. I. Mueller[2], Rumiana Dimova[2], Ruben Serral Gracia[2], Eberhard Unger[3] and Reinhard Lipowsky[2]; [1]Center for Theoretical Biological Physics, UC San Diego, La Jolla, California; [2]Max Planck Institute of Colloids and Interfaces, Potsdam, Germany; [3]Leibniz Institute for Age Research - Fritz Lipmann Institute, Jena, Germany.

Within cells, molecular motors often work in small teams to transport cargoes over large distances or to generate large forces. We have studied this type of motor cooperation both theoretically and experimentally using a stochastic model for motor cooperation based on the known properties of single motor molecules and in vitro bead assays with latex beads that were incubated with varying concentrations of kinesin-1. The number of motors pulling the beads were determined by a combination of fitting the experimental results with our model and dynamic light scattering experiments to determine the size of the motor-covered beads. For the kinesin concentrations used in the experiments, the size of the motor teams pulling a bead was found to be in the range of 1-7 with average team sizes between 1 and 3. Our theoretical and experimental results show that cargo run lengths are greatly increased when the cargo is pulled by an increasing number of motors. The average run length of a cargo pulled by N motors is approximately given by the run length of a single motor times c^N/N with c~5 according to our experiments. We also determined the run length distributions, which for cargoes pulled by several motors are given by sums of exponentials. In contrast, our experiments indicate that the cargo velocity is independent of the number of pulling motors, at least in aqueous solution. (For a highly viscous solution, our theoretical results however predict an increase of the cargo velocity with increasing number of pulling motors.) We propose that the cooperation of several motors facilitates the control of cargo movement, as switching the number of pulling motors constitutes a mechanism to tune parameters of cargo motility such as cargo processivity or pulling forces. Our study provides a framework to study such regulatory mechanisms and to explore their potential for technological applications.

4:45 PM FF2.8

Unexpected Velocity-dependent Cargo Loading onto Molecular Shuttles. Ashutosh Agarwal and Henry Hess; Materials Science and Engineering, University of Florida, Gainesville, Florida.

Molecular shuttles based on biomolecular motors and their associated filaments are being developed to function as conveyor belts in the molecular factories of the future. An essential design element is cargo loading onto these shuttles. In this work, we demonstrate that molecular shuttle velocity has to be optimized to facilitate cargo attachment of nanospheres via biotin-streptavidin linkages. Kinesin motor proteins were first adsorbed to a casein precoated surface. Biotinylated microtubules then adhered to the kinesin and were subsequently coated with rhodamine-labeled streptavidin at saturating dosages. The microtubule gliding velocity was varied between 50 nm/s and 450 nm/s by changing the kinesin substrate ATP concentration. Finally, biotinylated fluorescein-labeled nanospheres were added in concentrations ranging from 25 pM to 100 pM, which resulted in surface densities of 0.15 to 0.9 nanospheres per square micrometer. Nanospheres got loaded onto microtubules only as a result of collisions between gliding microtubules and nanospheres attached to the surface. Binding of nanospheres from solution to moving microtubules was never observed, and stationary microtubules (in the absence of ATP) did not capture nanospheres from solution. For purposes of loading of cargo onto moving shuttles, we discovered an unexpected optimum (250 nm/s) for the shuttle velocity. If the sticking probability for a microtubule-nanosphere collision were velocity-independent, the attachment rate would increase linearly with microtubule gliding velocity. However, the probability of the biotin-streptavidin bond to reach the strongly bound equilibrium state drops off with decreased time of contact, which in turn is inversely proportional to the shuttle velocity. The combination of increasing collision rate and decreasing sticking probability explains why we observe an increase in attachment rate of cargo to moving shuttles with increasing velocity until about 250 nm/s, after which it starts decreasing and drops to almost zero for shuttles moving at 500 nm/s. This contribution will focus on the experimental details of our velocity dependent loading experiments and our explanation of the existence of an optimum in shuttle velocity on the basis of the complex binding energy landscape of the biotin streptavidin linkages. Our efforts in optimizing the cargo loading onto moving shuttles reveal the “glue-like” behavior of biotin-streptavidin linkages. Bonds which are subjected to pulling forces immediately after formation are much weaker than the bonds which have been given a certain curing time to achieve their ultimate strength.

SESSION FF3: Poster Session: Molecular Motors, Nanomachines, and Active Nanostructures
Chairs: Amar Flood, Henry Hess and Heiner Linke
Tuesday Evening, March 25, 2008
8:00 PM
Salon Level (Marriott)

FF3.1

Functionalized Hybrid Structures for Active Molecular Electronics: Experimental Investigation and Theoretical Study. Kabeer Jasuja[1], Arthur Thompson[2], Mark Battig[1] and Vikas Berry[1]; [1]Department of Chemical Engineering, Kansas State University, Manhattan, Kansas; [2]Department of Electrical Engineering, Kansas State University, Manhattan, Kansas.

Molecular electro-mechanical-systems (MoEMS) are recently gaining a lot of interest due to their controllable functionality and potential applications in sensors and biomedicine. MoEMS evolves from molecular electronics and molecular mechanics. A number of techniques have been used to sandwich molecules between electrodes, for example STM, AFM and break junctions and have helped develop understanding of molecular electronics. There has also been a keen interest in the study of ‘active’ molecular systems like azo-polymers, rotaxane, molecular motors etc, which have been studied using AFM, liquid crystals etc. Here we present a study of a novel MoEMS system where ‘active’ molecules are sandwiched between metal nanoparticles which act as flexible electrodes. A novel fabrication process enables such an integration of flexible-nanoelectrodes and active-molecules. The mechanically-active molecular-links are excited to produce electromechanical response. We will demonstrate the response of these molecular opto-electromechanical structures and will also show a chemical sensor based on these MoEMS.

FF3.2

Photoreorientation of Light-Addressable, Azobenzene-Based, Photomechanical Monolayers. Joseph M Dahdah[1], T. E. Furtak[1], D. M. Walba[2], G. Fang[2], Y. Yi[2], J. E. Maclennan[2] and N. A. Clark[2]; [1]Physics, Colorado School of Mines, Golden, Colorado; [2]Physics, University of Colorado, Boulder, Colorado.

Azobenzene-based photomechanical monolayers have received a great deal of attention for potential as platforms for light-addressable nano-engineered structures in bioscience, photonics, and display technologies. We have developed an aminoazobenzene material, derived from methyl red, which forms high quality, covalently anchored monolayers on glass. These monolayers demonstrate unusually high sensitivity to polarized light, which controls the molecular orientation distribution through optical anisotropy of the trans-cis isomerization. In an effort to understand and optimize this phenomenon we are studying the influence of the two-dimensional molecular field on the structure and light-driven reorganization of the monolayer. To determine the orientational order parameters of this surface and their modification upon illumination we have employed a combination of optical techniques: second harmonic generation, spectroscopic ellipsometry, and dichroism spectroscopy. These optical studies are analyzed in terms of a photochemical model incorporating all known mechanisms for photoorientation. The model addresses optical local field and mean molecular field effects in a self-consistent manner. --Supported by NSF through the Liquid Crystal Materials Research Center: DMR-0213918

FF3.3

Kinetics of a DNA-mediated Docking Reaction Between Tethered Vesicles. Yee-Hung Mark Chan[1], Peter Lenz[2] and Steven G Boxer[1]; [1]Chemistry, Stanford University, Stanford, California; [2]Physics, Philipps-University, Marburg, Germany.

Recognition and binding between biological membranes are generally tightly regulated processes, and characterizing these reactions is important for many problems including cell adhesion and vesicle fusion. A model system consisting of tethered vesicles was used to measure the kinetics of docking of vesicle populations displaying complementary DNA oligonucleotides which are linked to the lipid anchor at the 5' end.* Vesicles were first tethered to a supported bilayer by using a complementary sequence pair A and A' by using a microfluidic device which creates physically separated populations of tethered vesicles. After the vesicles diffuse and mix, epifluorescence microscopy can capture collisions between pairs of vesicles, and docking mediated by B and B' results in the vesicles' colocalization and tandem diffusion as shown schematically. The probability, Pdock, that a collision leads to docking was extracted from the data using a lattice-diffusion model of the system, and shows a dependence on the sequence and the number density of DNA per vesicle. These trends are explained by a reaction model which gives a scaling relationship between Pdock and

relevant parameters. * Yoshina-Ishii et al., JACS, 125, 3696 (2003); 127, 1356 (2005); Langmuir, 22, 2384 & 5682 (2006).

FF3.4
Transferred to FF2.8

FF3.5
DNA-mediated Fusion of Lipid Vesicles. Yee-Hung M. Chan, Bettina van Lengerich and Steven G. Boxer; Chemistry, Stanford University, Stanford, California.

Hybridization of DNA-oligonucleotides coupled to lipids at the 5' end can be used tether liposomes to supported lipid bilayers* and to mediate docking**, but fusion has not been observed because the duplex DNA acts as a spacer between the two membranes. A modified synthesis allows coupling of the lipid to the 3' end of the DNA strand. Now, hybridization between 5' and 3' DNA-lipids on different vesicles may bring the membrane surfaces closer together. This approximates the geometry believed to be relevant in SNARE protein-mediated neuronal fusion. Reaction of vesicles displaying complementary DNA linked at the 5' and 3' ends leads to both lipid and content mixing, indicating DNA-mediated vesicle fusion is occurring. The rate of mixing shows a dependence on the copy number and sequence of the complimentary DNA. Progress towards visualizing individual fusion events using mobile vesicles tethered to supported bilayers by fluorescence microscopy is described. * Yoshina-Ishii et al., JACS, 125, 3696 (2003); 127, 1356 (2005); Langmuir, 22, 2384 & 5682 (2006). ** Chan et al. submitted

FF3.6
Lattice Simulations of Microtubule “Nanospool” Formation Dynamics. Jasmine Claren Davenport, Henry Hess and Simon Phillpot; Materials Science & Engineering, University of Florida, Gainesville, Florida.

Biotinylated microtubule filaments partially coated with streptavidin and gliding on surface-adhered kinesin motor proteins converge to form linear “nanowire” and circular “nanospool” structures. We present a computer simulation method that models the dynamics of microtubule gliding and interaction. In this method, each microtubule is composed of a head, a number of body segments, and a tail. The microtubules move across a hexagonal lattice with the direction of motion of the head segment being determined probabilistically; the body and tail segments follow the path of the head. The surface density of microtubules, their lengths, their rigidities and their modes of interaction can all be varied. The analysis of the motion and interaction of the microtubules over large distances allows statistically meaningful data to be obtained which can be compared to experimental results, and will aid in predictions of the formation of nanowires and nanospools. This work is supported by NSF-DMR 0645023.

FF3.7
Electrically Switchable Liquid Crystal Polymer Rod Actuators. Matthew S Shafran, Kostas A Sierros and Darran R Cairns; West Virginia University, Morgantown, West Virginia.

We have successfully fabricated anisotropic liquid crystal polymer nanorods that can be re-orientated by an applied electric field. The nanorods, 200 nm in diameter and a maximum of 60 μm in length, were produced by a template synthesis technique. A reactive liquid crystal monomer was filled into porous Anopore membranes. The reactive monomer liquid crystal was polymerized by UV light while the liquid crystal remained in the nematic temperature range. The polymerization process permanently “freezes” the orientational order of the confined liquid crystal molecules, producing nanorods that are temperature independent after curing. The curing is kept in the nematic range to ensure proper orientation alignment in the pore of the membrane, where the responsive nature of the rods can be tailored by appropriate surface anchoring. The rods were suspended in low viscosity silicone oil and injected into indium tin oxide coated glass cells. Both DC and AC electric fields were applied to the electro-optical glass cells. We will discuss the trends of the switching times (time to change orientation from horizontal to vertical) of the nanorods in varying DC field strengths; which can be controlled by voltage. The switching time has been observed to be as fast as 0.1 seconds and the threshold voltage has been as low as 5 volts. The relaxation time (time to change orientation from vertical to horizontal) will also be explored for the various DC field strengths. We will discuss other factors affecting switching times including nanorod diameter and length, dispersion fluid, curing temperature, and applications of electric or magnetic fields during curing. AC electric fields have been shown to vibrate and rotate the nanorods, which opens up a range of applications in microfluidics.

FF3.8
Engineering a Kinesin Biomolecular Motor for Controlling Cargo-specific Transport and Materials Assembly. Adrienne C. Greene[1,2], Amanda Carroll-Portillo[1] and George D. Bachand[1]; [1]Biomolecular Interfaces and Systems, Sandia National Laboratories, Albuquerque, New Mexico; [2]Department of Biology, The University of New Mexico, Albuquerque, New Mexico.

Living systems use energy-driven processes to direct the non-linear assembly of nanostructured materials. In particular, biomolecular motors drive the transport and assembly of a variety of materials within a cell’s nanofluidic environment. These systems rely on complex signaling pathways to direct motor function and ultimately the transport of molecular building blocks. Kinesins represent one class of motor proteins within cells that are responsible for transporting molecules throughout the cytoplasm along the microtubule cytoskeleton. The kinesin-microtubule system has also been studied with respect to transporting and assembling materials in hybrid, nanoscale systems. Integrating kinesin transport into active materials assembly, however, requires two key elements: (1) the ability to regulate motor function and (2) ability to selectively define cargo loading. To address the first element, we have demonstrated the ability to control kinesin motor function using a genetically engineered chemical switch. A zinc-binding domain engineered into the neck-linker region of kinesin provided a reversible means for regulating motor functionality. Kinesin motility was completely inhibited in the presence of divalent zinc cations; motor function resumed fully upon chelation of the zinc. The mutant kinesin motor remained stable over several sequential cycles of inhibition and restoration of motility. This switch mutant motor also responded to a number of other divalent metal ions and a variety of chelators. A unique feature of this mechanism is the ability to control motor function while maintaining the energy supply in the system (i.e. ATP). To address the second requisite element, we have begun engineering a chimeric kinesin motor that, in addition to the chemical on/off switch, contains a specific cargo-binding site at the tail (i.e., cargo-carrying) domain. A gene encoding the biotin carboxyl carrier protein subunit (BCCP) from *Escherichia coli* has been introduced at the C-terminus of the kinesin switch mutant using genetic engineering methods. This will create a biotin-streptavidin interaction site on the tail of the switchable mutant kinesin. Once completed, this new kinesin motor protein will be controllable through chemical switching and will enable cargo to be selectively transported in nanofluidic architectures. Sandia is a multiprogram

laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

FF3.9

Adsorption and Function of Heavy Meromyosin Motors Related to Surface Charge and Contact Angle. Nuria Albet Torres[1], John O'Mahony[1], Christy Charlton[1], Martina Balaz[1], Patricia Lisboa[2], Teodor Aastrup[3], Alf Månsson[1] and Ian A. Nicholls[1]; [1]School of Pure and Applied Natural Sciences, University of Kalmar, Kalmar, Sweden; [2]Institute for Health and Consumer Protection, European Commission - Joint Research Centre, Ispra, Italy; [3]Attana AB, Stockholm, Sweden.

We have recently developed a model for the mode of adsorption of heavy meromyosin (HMM) on surfaces of different chemistries. The model was designed particularly to account for motor functionality (HMM induced sliding of actin filaments). In our most recent work we have used In Vitro Motility Assays (IVMA) and Quartz Crystal Microbalance (QCM) techniques in order to quantify motor functionality and adsorption behavior on several pure and silanized glass surfaces. Prior to use in the IVMA, we characterized the surfaces by contact angle goniometry, Atomic Force Microscopy (AFM) and ζ-potential measurements. The main result was the observation of a silane independent correlation between motor function (actin sliding velocity) on one hand, and surface hydrophobicity and charge on the other. Specifically, we observed an increased filament velocity with increasing contact angle (up to ~80 degrees) and decreasing negative ζ-potential for all studied surfaces. The AFM roughness data were uncorrelated with filament velocity and contact angle, allowing us to conclude that roughness on the observed level (rms roughness < 3 nm) had no effect on motor function. Regarding the QCM results, we detected a lower adsorbed HMM mass on the more hydrophobic surfaces compared to the hydrophilic ones. However, in accordance with the IVMA results, we found a higher increase in mass on the more hydrophobic surfaces with HMM when these were incubated with actin filaments. The main feature of the proposed model is that the difference in motor functionality between different surfaces is due to different modes of HMM adsorption with only minor changes in the amount of adsorbed HMM. Since the actin binding HMM heads have positively charged parts they may electrostatically interact with the more negatively charged surfaces (equivalent to more hydrophilic surfaces in the present study) bringing the heads close to the surface and preventing them from binding to, and propelling the actin filaments. Consistently, the more hydrophobic the surface the more of the "heads-up" (functional) and less of the "heads-down" (non-functional) HMM configurations. The results are considered in relation to the appropriate selection of surface chemistries for nanostructured surfaces designed to guide HMM-propelled actin filaments in nanotechnological applications.

FF3.10

Experimental Realization of a Feedback Controlled Brownian Ratchet. Benjamin Jose Lopez, Erin M Craig, Nathan Kuwada and Heiner Linke; Physics, University of Oregon, Eugene, Oregon.

A flashing ratchet is a Brownian motor that rectifies thermal fluctuations of diffusive particles through the use of a time-dependent periodic and asymmetric potential. It has been shown theoretically that a feedback-controlled flashing ratchet has a center of mass speed as much as one order of magnitude larger than the optimal periodically flashing ratchet [1]. For dimeric molecular motors, feedback control mechanisms are likely to be crucial to achieve processivity and can help explain experimental data [2]. Our immediate goals for this project are to implement the first feedback ratchet, and to test theory that predicts the efficiency of different feedback algorithms as a function of feedback delay. In particular, there is a maximum displacement feedback scheme [3] that predicts for small N to provide an even larger center of mass velocity than the threshold average force scheme described in reference 1. In our experiment a scanning line optical trap setup is used to transport micron-sized particles using a feedback controlled Brownian ratchet. This system can create potential energy landscapes that realize the steps of a Brownian ratchet process. At the time of writing, we have a scan line of 20 microns in length that stably traps 0.9 micron silica spheres. A flat potential with variations on the order of kT, and a ratchet potential with two-micron periods and an asymmetry of 1/3 have been realized. A ratchet depth of 40 kT per watt of output laser power has been measured. Real time particle tracking at 100 Hz is achieved through software based video analysis. To see a significant effect for small N the feedback delay time must be less than 0.05 L^2/D [4], where L is the ratchet period length and D is the diffusion constant. With current experimental parameters this value is 21 ms. In this setup feedback has a minimum implementation delay of 4 ms, and feedback effects should be experimentally observable. We will present speed of ratchet velocity for different feedback algorithms and particle numbers, and compare these results to modeling results. Another application of this setup will be to experimentally model the motion of linear, two headed, processive molecular motors. It is difficult to systematically vary parameters in studies of biological molecular motors and using a model system can help understand the performance of different operational principles for molecular motors. [1] F.J. Cao, L. Dinis, and J.M.R. Parrondo, Phys. Rev. Lett. 93, (2004). [2] M. Bier, BioSystems 88, 301 (2007). [3] E.M. Craig, N. Kuwada, B. Lopez, H. Linke, to be published (2007). [4] E.M. Craig, B. Long, J.M. Parrondo, H. Linke, to appear in Europhys. Lett.(2007).

FF3.11

Giant 'Dry' Actuation of PEDOT:PSS Thin Films. Dimitri S.H. Charrier, Lukas Brinek, Martijn Kemerink and Rene A.J. Janssen; Eindhoven University of Technology, Eindhoven, Noord Brabant, Netherlands.

The empirical research in the field of organic actuation aims at developing, amongst others, biomimetic materials to be used as muscle-like actuators or shape-memory alloys, with conjugated polymers as active materials. The operational principle of these wet devices is (ionic)current-driven mass transport through the polymer network, with counter charges flowing through the electrolyte, leading to volume changes up to ca. 100 %. In this work we show that thin films of the oxidatively doped conjugated polymer blend PEDOT:PSS exhibit a huge (up to 400 %) and reversible actuation in a two-terminal configuration, i.e. without the need to submerge the device in an electrolyte. Experiments are performed on interdigitated-finger devices with channel lengths ranging from 1 to 20 um under ambient conditions. The actuation and current flow are followed in real space and time by simultaneous AFM and current measurements. By varying the relative humidity of the environment, the packing density of the PEDOT and PSS chains and the ion background, both the actuation speed as well as its magnitude and sign could be varied. Based on these measurements, we propose two dominant redox reactions. A simple model enables us to relate both the actuation rate and the maximum actuation to the device geometry and the ionic part of the device current.

FF3.12

Fatigue and Wear of Microtubules Induced by Kinesin Motor Activity. Yoli Jeune, Krishna Nittala and Henry Hess; Materials Science Engineering, University of Florida, Gainesville, Florida.

The kinesin-powered molecular shuttle system is one of the more mature man-made active nanosystems available. In this system, microtubules are employed as molecular shuttles to integrate biological nanomachines and enable controlled transport of molecules and other microscopic cargo in synthetic environments. In typical designs, kinesin motor proteins are adhered to a surface and fueled by ATP; microtubules glide over the motors. Significant advances have been made and solutions exist for cargo loading, shuttle guiding in microfabricated channels and controlled activation; however, degradation of microtubules incorporated in these active nanomechanical systems, due to wear and fatigue, has not been studied. Understanding the degradation mechanism of nanoscale structures is crucial for applications involving biomolecules. Previous and current studies of nanoscale degradation have been limited to static systems. In these studies, degradation is frequently characterized by chemical processes. However, in active, dynamic nanosystems internal motion and mechanical forces generated within can lead to wear of its components. This is similar to how the operation of a car engine will cause specific degradation processes which would not occur if the engine sat unused. In this study, fluorescently-labeled microtubules, shuttled by kinesin motors in a flow cell, are used as a model system for the investigation of nanoscale degradation. Degradation of microtubules with varying kinesin motor activity was investigated. Kinesin motor activity was controlled by varying the concentration of ATP fuel. Fluorescence microscopy was used to observe microtubule degradation in the flow cell. The motor-related degradation was isolated by minimizing degradation due to chemical processes such as depolymerization and oxidative damage. Microtubules moved by active motors experienced extensive degradation as opposed to microtubules held by inactive motors. Microtubule degradation is described by the change in number density and length distribution with time. The change in number density and length distribution can be described as occurring in two phases: landing and breakage. Degradation of microtubules due to breakage increases with increased motor activity. A plot similar to the S-N curve of metallic systems is used to illustrate the failure mode of microtubules. A theoretical model for the degradation process will be presented to lay a foundation for creating a conceptual framework. Lastly we will discuss the implications for technological and biological systems.

FF3.13

Enzyme Assisted Formation of Peptide Nanotubes. Richard James Williams[1,2] and Rein Ulijn[1,2]; [1]Materials Science, Manchester University, Manchester, United Kingdom; [2]Manchester Interdisciplinary Biocentre, Manchester University, Manchester, United Kingdom.

Self-assembly as an approach to produce complex molecular architectures is commonplace in biology. Despite significant advances in the field, the complexity that can be achieved in the laboratory is limited by comparison. Defect free, reproducible, homogeneous and spatially organised self-assembled structures are essential for applications as diverse as 3D cell culture, biosensors, organic electronics and nanoscopic devices. It is a significant challenge to ensure that molecular building blocks assemble in a desired arrangement in a specific arrangement from a directed locus. Self-assembly is driven by the use of enzymes to convert non-assembling precursors into assembling components allows the process to occur under otherwise constant conditions of pH, ionic strength, solvent polarity and temperature. We recently demonstrated a first example of enzyme-assisted self-assembly under thermodynamic control where enzyme reaction and self-assembly are necessarily coupled. Thermolysin from Thermoproteolyticus rokko, was used to drive the self-assembly via condensation of aromatic amino acid derivatives containing fluorenylmethoxycarbonyl (Fmoc) protecting groups, and di-peptide components (diphenylalanine and dileucine) [JACS, 2006]. Aromatic short peptide derivatives that result from the condensation reaction are thought to self-assemble to nanofibrous structures stabilised by Π-Π stacked aromatic groups and anti-parallel β-sheets of peptide components. Fibrils of 5 nm widths can be observed propagating with fibril length increasing over time. The ability of the system to reversibly reach an equilibrium assembled structure (i.e. self-correction), representing a single free energy minimum, is further demonstrated by comparison of peptide production over time, measured by HPLC, the formation of structure, measured by fluorescence spectroscopy and circular dichroism [Advanced Materials, 2008]. TEM analysis demonstrated that assembly and nucleation are confined to the direct vicinity of enzyme molecules. Because self-assembly enables the enzymatic formation of building blocks one would expect self-assembled structures to nucleate and grow exclusively where enzymes assist in nucleation and assembly. This spatiotemporal confinement could be visualised at the early stages of self-assembly by TEM. The formation of spherical objects of 25-35 nm size was observed. Each nanosphere contains one, or a small number of, enzyme molecule(s) (diameter <2 nm). This coupling of nucleation and propagation with enzyme locus presents opportunities for site specific fibril formation through the use of immobilised enzymes to create directionally defined nanofibres.

FF3.14

Photoresponsive Liquid Crystal Elastomers. Timothy John White[1,2], Vincent P. Tondiglia[1,3], Hilmar Koerner[4,5], Richard A. Vaia[4], Svetlana Serak[6], Vladimir Grozhik[6], Nelson Tabiriyan[6] and Timothy J. Bunning[1]; [1]AFRL/RXPJ, WPAFB, Ohio; [2]General Dynamics, WPAFB, Ohio; [3]SAIC, WPAFB, Ohio; [4]AFRL/RXBP, WPAFB, Ohio; [5]Univ. of Dayton Research Institute, WPAFB, Ohio; [6]BEAM Co., Winter Park, Florida.

A liquid crystalline elastomer (LCE) containing both main chain and side chain azobenzene mesogens exhibits bidirectional actuation upon illumination of low power polarized laser light. Large angle deformation (+/-70 deg), the direction of which is controlled by the laser polarization, is achieved in less than 300 ms. We recently have shown that at high laser intensity, a shape-restoring monodomain azobenzene LCE can controllably and reversibly oscillate over a large range (120 deg) at a frequency of 23 Hz. Finally, recent work on the development of a high modulus (> 1 GPa) LCE photoactuator formed from the copolymerization of an LC crosslinker and a monofunctional azobenzene LC monomer will also be presented. The resulting copolymer is a side-chain LCE that can bend up to 85 deg in nearly 200 ms.

FF3.15

Abstract Withdrawn

FF3.16

Abstract Withdrawn

FF3.17

Efficiency Considerations of Synthetic Molecular Machines under Redox Control. Amar H Flood, Kumar Parimal, Kristy McNitt and Albert Fahrenbach; Chemistry, Indiana University, Bloomington, Indiana.

Redox-driven molecular switches based on pseudorotaxanes and rotaxanes form a basis for the development of molecular machines. Towards these ends, copper ions provide opportunities to take advantage of dynamic self-assembly which can be made to display bistable behavior depending upon their oxidation states, copper(+1) or copper(+2), thereby allowing for the relative movements of molecular subcomponents, called ligands. These copper systems are developed through the formation and evaluation of pseudorotaxanes, in which a rod-shaped (R) component is encircled by a ring-like component and both are held in place by the copper ion. It was a surprise to us, therefore, when we discovered a switching process in a [2]pseudorotaxane -- where only one ring encircles the rod -- that arises from the reduction, and not the copper oxidation. Our results from electrochemistry indicate that upon reduction of the rod component to its singly-charged anion, R(-1) one of the rings of a neighboring [2] pseudorotaxane leaves and joins to encircle the reduced rod in a "partner swapping" exchange to make a reduced [3]pseudorotaxane where there are now two rings encircled the rod. The driving force for this process is electrostatic, the two rings also bring two copper monocations providing a greater stabilization of the monoanion located on the central rod component. When the [3]pseudorotaxane is reoxidized, one of the rings return making the entire cycle fully reversible. This switching can be made to occur fast with a lot of energy input or slowly with less energy input. These two regimes (fast or slow) will be evaluated from the context of efficiency and related to two extreme mechanisms of power strokes and Brownian ratchets.

FF3.18
Abstract Withdrawn

FF3.19
Fabrication of Thermoresponsive Copolymer-grafted Surface for Insect Cell Driven Actuator. Yui Sakuma[1], Yoshitake Akiyama[1], Kikuo Iwabuchi[1], Yoshikatsu Akiyama[2], Masayuki Yamato[2], Teruo Okano[2] and Keisuke Morishima[1]; [1]Tokyo University of Agriculture and Technology, Tokyo, Japan; [2]Tokyo Women's Medical University, Tokyo, Japan.

Our group has already proposed a novel mechano-bionic system using a living component as a micro driving source that is interfaced between mechanics and biology. In the system, cardiomyocytes are utilized as a mechanical component which can autonomously contract by the chemical energy. The bio-device needs the precise control of temperature and pH in medium in order to keep the cardiomyocyte beating, which makes it hard for practical use. As an alternative driving component, we focused on an insect heart called a dorsal vessel. The insect dorsal vessel-derived cells are tolerant over culture conditions e.g. temperature, pH compared to the cardiomyocyte. Therefore we approach a novel and environmentally robust mechano-bionic system using the insect cells. The mammalian cell sheet is fabricated with cell sheet engineering, in which the surface of the culture dish grafted with thermoresponsive polymer, poly N isopropylacrylamide (PIPAAm), changes from hydrophobic to hydrophilic by decreasing temperature from 37 deg C to below the lower critical solution temperature (LCST), the hydrophobic/ hydrophilic phase transition temperature, 32 deg C of thermoresponsive polymer. Insect cells, however, are cultured at 25 deg C. In this study, we show the design and evaluation of thermoresponsive polymer-grafted culture dishes for the insect cell sheet. To lower the LCST to the extent of the cultivation temperature is possible by incorporating a hydrophobic monomer into PIPAAm. Therefore, as a hydrophobic monomer, tert-butylacrylamide (tBAAm) was used and co-polymer, poly-N (isopropylacrylamide(IPAAm)-co-tert-butylacrylamide(tBAAm)) -grafted culture dishes was fabricated for insect cells. Then that the LCST of the copolymer-grafted dishes is below 32 deg C was confirmed by measuring the contact angle on the dishes using sessile drop method. The insect cell lines of a tiger mosquito (NIAS-AeAl-2) were cultured with MM in the presence of 3% FBS on the PIPAAm-, and the copolymer-grafted dishes at 25 deg C. On the copolymer surfaces, the cells attachment was confirmed but on the PIPAAm surface was not. However tried to harvest the cell sheet by lowering temperature at 20 deg C, the cells detachment in the sheets was not observed. To harvest the insect cell sheet, we are due to coating the extracellular matrix and culturing the insect dorsal vessel-derived cells on the surface. By fabricating the insect cell sheet, a novel autonomous and environmentally-resist mechano-bionic system will be expected.

FF3.20
Photomodulation of Reactivity using Molecular Switches: Towards the Development of Novel Functional Materials. Vincent Lemieux and Neil R. Branda; 4D LABS, Department of Chemistry, Simon Fraser University, Burnaby, British Columbia, Canada.

We recently described a versatile approach, based on molecular photoswitching strategies, for photoreleasing active compounds from inert "masked" forms.(1) Low-energy visible light converts thermally stable "locked" compounds into thermally unstable forms that undergo spontaneous fragmentation. The rationally designed photoresponsive architecture permits selective stimulation of various compounds using different light sources and thus allows selective and sequential release of payloads. This technology offers an elevated level of control compared to existing systems that undergo spatial and temporal photorelease and has the potential to deliver pharmaceuticals and other biologically relevant molecules as well as designer reagents for synthesis and photolithography. Our progress towards the development of practical applications will be presented. (1) V. Lemieux, S. Gauthier, N.R. Branda, Angew. Chem. Int. Ed. 2006, 45(41), 6820.

FF3.21
Direct Imaging of Electrostatic and Electromechanical Interactions in a Conductive Liquid Environment. Sergei V. Kalinin[1], Brian J Rodriguez[1], Philip D. Rack[1,2], Katya Seal[1] and Stephen Jesse[1]; [1]Oak Ridge National Laboratory, Oak Ridge, Tennessee; [2]University of Tennesse, Knoxville, Tennessee.

Probing and controlling electromechanical transformations on nanometer and molecular levels is an enabling component for probing bias-controlled biological systems, molecular shape changes in electrochemical transformations, and ultimately developments of molecular electromechanical devices. Scanning Probe Microscopy offers a pathway towards probing the electromechanical processes in molecular and biological systems. Achieving this goal requires the development of SPM methods capable of electromechanical measurements in a conductive liquid, including (a) the development of probes capable of concentrating an electric field within the tip-surface junction and (b) development of resonant excitation modes insensitive to phase content of the signal. Here we study the ac and dc field distribution established by a conductive tip in liquid as a function of conductivity and frequency. It is shown that the use of high (>100 kHz) frequencies allows field concentration in the tip-surface junction and high-resolution electromechanical imaging. At the same time, dc fields are essentially delocalized. The shielded probes are developed to concentrate the dc field. The electromechanical imaging of a number of model systems in various liquid environments is demonstrated. 1. B.J. Rodriguez, S.Jesse, A.P. Baddorf, S.H. Kim, and S.V. Kalinin, Phys. Rev. Lett. 98, 247603 (2007). 2. B.J. Rodriguez, S. Jesse, A.P. Baddorf, and S.V. Kalinin, Phys. Rev. Lett. 96, 237602 (2006). The research is supported (SVK, KS, BJR, SJ) by the Center for Nanophase Materials Sciences, Oak Ridge National Laboratory, managed and operated by UT-Battelle, LLC for the Office of Basic Energy Sciences, US Department of Energy.

FF3.22

Nanoscale Self-Assembly Of Bimetallic "Janus" Particles into Dimers and Higher Structures. Shengrong Ye and R. Lloyd Carroll; West Virginia University, Morgantown, West Virginia.

Photonic crystals are periodic arrays of dielectric materials that allow the manipulation of light in much the same way that semiconductor materials allow the manipulation of electrons. The use of asymmetric components as building blocks in photonic crystals breaks degeneracy in the photonic material, opening the pathways to sophisticated optical control systems. Our previous experiments show that bimetallic "Janus" particles coated with Au and Pt on each hemisphere can be successfully fabricated. These colloidal "Janus" particles were formed by the electron deposition of gold and platinum on each side of the polystyrene or silica beads. The overall strategy for self-assembly of these "Janus" particles is to independently functionalize the metal surfaces with chemically distinct functional groups to produce beads that are associative and specific for one another. In this research, we will demonstrate the chemical modification of bimetallic "Janus" particles by using two distinct surface modification motifs. Specifically, selective functionalization was achieved through a thiol linkage on the Au side and an isocyanide linkage on the Pt side. Interaction of beads with specific reaction pairs on their surfaces produces dimers of distinct types, as well as defect structures of higher clusters and chains. Distinct clusters may also be produced through the use of emulsion techniques. The size and configuration of the colloidal clusters is controllable by tuning the w/o ratio and other conditions. This is also a general approach to make particles with different chemical properties. Furthermore, the ability to synthesize particles with different surface chemistry provides the opportunity to introduce multiple chemical functionalities, such as enzymes, DNA and other chemical structures, by exploiting the selective binding of different ligands to the different positions. Interestingly, we also found a silica ring at the equatorial position, which is possible to endow with a third chemical functionality.

FF3.23

Computer Simulation of Molecular Shuttles Propelled by Motor Proteins. Takahiro Nitta[1], Akihito Tanahashi[1], Yu Obara[1], Motohisa Hirano[1], Maria Razumova[2], Michael Regnier[2] and Henry Hess[3]; [1]Dept. Math. and Design Eng., Gifu University, Gifu, Gifu, Japan; [2]Dept. Bioengineering, University of Washington, Seattle, Washington; [3]Dept. Materials Sci. and Eng., University of Florida, Gainesville, Florida.

Myosin/actin and kinesin/microtubule have been utilized as molecular shuttles for Lab-on-a-chip devices. Molecular shuttles are cytoskeletal filaments loaded with cargo and propelled by the associated motor proteins along predetermined tracks to deliver cargo to specific destinations. Both types of molecular shuttles have their unique advantages and disadvantages due to intrinsic properties of the motor proteins and the filaments. For example, a myosin/actin-based molecular shuttle can glide faster but needs narrower guiding tracks than a kinesin/microtubule-based one. Hence, depending on the specific tasks of the device, appropriate molecular shuttles should be selected and integrated with suitable module designs. However, at present the choice of shuttle type and the design of module structures are carried out using engineering intuition and experimental trial and error. We previously developed a computer simulation for kinesin/microtubule-based molecular shuttles. This computer simulation was shown to be useful in designing module structures for kinesin/microtubule-based molecular shuttles. In the present study, we extend the computer simulation to deal with myosin/actin-based molecular shuttles. To this end, by performing in vitro motility assay, we measured the required parameters - time-averaged velocity, motional diffusion coefficient and persistence length of actin/myosin-based molecular shuttles. The computer simulation reproduced experimental results reported by other groups. Thus, our computer simulation can be applied to selecting appropriate molecular shuttles and module designs in silico.

FF3.24

Nanoscale Assembly and Measurement of Molecular Machines. Tao Ye, School of Natural Sciences, University of California, Merced, Merced, California.

Significant progress has been made in creating synthetic molecules capable of internal conformational changes in response to external stimuli in the solution phase. However, their single molecule properties in technologically relevant environments, such as at interfaces and in nanoscale assemblies remain to be investigated. Working with synthetic chemists, we have probed and controlled molecular machines down to the single molecule level. I will describe two types of molecular motions, linear motion by rotaxanes driven by electrochemistry, and light-driven switching motion by azobenzene derivatives. Critical to single molecule observations and control are purposeful molecular design and nanoscale assembly that determine the orientation, spacing and steric interactions of these single molecule machines. Molecules and assemblies can perform desired motion only when they are properly interfaced to their nanoscale environments.

FF3.25

Towards Electromechanical Imaging of Cellular Systems in a Liquid Environment. Brian J. Rodriguez[1], Gary Thompson[3], Sophia Hohlbauch[2], Irene Revenko[2], Nick Geisse[2], Alexey Vertegel[3], Roger Proksch[2] and Sergei V. Kalinin[1]; [1]Materials Sciences and Technology Division and the Center for Nanophase Materials Sciences, Oak Ridge National Laboratory, Oak Ridge, Tennessee; [2]Asylum Research, Santa Barbara, California; [3]Department of Bioengineering, Clemson University, Clemson, South Carolina.

Coupling between electrical and mechanical phenomena is ubiquitous in biological systems, underpinning phenomena ranging from cardiac activity to outer hair cell stereocilia to energy storage in mitochondria. Investigating the electromechanical response of biological systems at the nanoscale will also improve our understanding of their functionality at the macroscale. The electromechanical probing of cellular systems thus can be used both as an imaging and characterization tool, as well as a first step in the development of artificial cell-based electromotors. However, probing electromechanics of cellular systems is traditionally impeded by the requirement of conductive liquid media necessary to support biological activity and cell viability. In this presentation, we will summarize recent progress on scanning probe microscopy imaging of electromechanical phenomena in biological samples under physiological conditions with advanced imaging and spectroscopic modes, including Piezoresponse Force Microscopy (PFM). These improvements include a better understanding of the conditions for electromechanical contrast in conductive solutions through the study of model ferroelectric systems. We will also present results on the local electromechanical probing of several model cellular and biomolecular systems in a liquid environment, including insulin and lysozyme amyloid fibrils, breast adenocarcinoma cells, and bacteriorhodopsin. The specific features of PFM operation in liquid are delineated and bottlenecks on the route towards single molecular resolution electromechanical imaging of biological systems will be discussed. This research is supported (SVK, BJR) by the Center for Nanophase Materials Sciences, Oak Ridge National Laboratory, managed and operated by UT-Battelle, LLC for the Office of Basic Energy Sciences, US Department of Energy.

FF3.26
Fabrication of Micro Bio-fabricated Actuator Powered by Cardiomyocyte. Hiroshi Horiguchi, Yoshitake Akiyama and Keisuke Morishima; Tokyo university of Agriculture and Technology, Tokyo, Japan.

Here, we propose a novel concept of fabrication process for micro bio-actuator powered by cardiomyocytes. We have already developed and reported a micro bio-actuator powered by cardiomyocytes such as a pump. The cardiomyocytes, which can contract spontaneously and convert chemical energy into mechanical energy efficiently without changing it into thermal energy, are considered as a high performance actuator. But, contractile force of single cardiomyocyte is inadequate to actuate micro robot and mechanical system. So the integration of the cardiomyocytes to generate high contractile force has been researched. In this study, we integrate cardiomyocytes such as muscle tissue to generate high contractile force of cardiomyocytes and apply bio-fabricated actuator to mechanical system. We suggest a micro cardiomyocyte gel structures as the integration of cardiomyocyte. The cardiomyocyte gel structure is cardiomyocyte culture in three dimensional gel structures utilized such as scaffold. The micro cardiomyocyte gel structure is deformed by the contractile force of cardiomyocytes in the three dimensional gel structures. Fabrication process of micro cardiomyocyte gel structure has four steps. First, a PDMS membrane with circular micro grooves is fabricated using photolithography. Second, the PDMS chamber is fabricated by attaching the PDMS membrane to a PDMS frame. Third, the liquid mixture consisting of isolated cardiomyocytes from neonatal rats, collagen type I prepared from rat tails, a basement membrane protein mixture and culture medium is poured into the circular casting molds and incubated for 45 to 60 minutes at 37 degree Celsius under 5% CO_2 atmosphere to allow hardening of the liquid mixture. After the incubation, 1.0 ml culture medium is poured into the PDMS chamber. After 7 days of culture, the PDMS chamber is attached to stretching device and stretched to generate high contractile force of cardiomyocytes for an additional 7 days. After stretching, we think that three dimensional gel structure contracts spontaneously. The prototype of micro cardiomyocyte gel structure on the surface of the PDMS membrane was observed using inverted microscope. First contraction of single cardiomyocyte in the gel structure was observed at 2 days. At 6 days, the cardiomyocyte gel structure condensed around the central cylinder within the PDMS membrane and contracted synchronously. The thickness of the gel structure was 200μm and its frequency was about 0.35Hz. In future, these devices will be one of the key components of self-powered medical and ubiquitous equipments.

SESSION FF4: Motors and Active Nanostructures from DNA, Proteins, and Cells
Chair: Henry Hess
Wednesday Morning, March 26, 2008
Room 3018 (Moscone West)

8:30 AM *FF4.1
Nucleic Acid-Based Nanomechanical Devices. Nadrian C Seeman, Baoquan Ding, Banani Chakraborty and Hongzhou Gu; Chemistry, New York University, New York, New York.

Structural DNA nanotechnology combines branched DNA motifs with cohesive ends to form objects, lattices and devices. It has been possible for many years to produce 2D arrays from a variety of DNA motifs that tile the plane. One of the chief goals of this approach is not merely to produce DNA arrangements, but to develop and organize functional species. Here we report robust multi-state devices and the interactions of devices within the context of 2D arrays. In the past, we developed a robust sequence-dependent DNA nanomechanical device, termed the PX-JX2 device. Its two states entail a half-rotation between one end and the other. We term the device robust, because it behaves like a macroscopic machine, and does not undergo any dissociation or multimerization in the course of its machine cycle. The device is controlled by the addition of particular strands to the system. Here, we have extended this device so that it has a third, robust state, in addition to the two states present previously. This third motion is a contraction, so that there are three transitions associated with its action: A half-rotation, a contraction and a screw rotation. In addition, we have developed a cassette that incorporates the PX-JX2 nanomechanical device. We have used eight different three-domain motifs (TX) connected 1-3 to form a lattice containing gaps that are flanked by sticky ends. The cassette contains sticky ends complementary to those in the lattice, enabling us to insert the cassette into the lattice. The cassette also contains a robot arm whose position switches with the state of the device. We demonstrate by atomic force microscopy (AFM) that the device is functional following insertion. We are able to observe the switching of the arm between states within the context of the lattice. This system opens the door to a variety of multi-state nanomechanical systems. This research supported by grants from the National Institute of General Medical Sciences, the National Science Foundation, the Army Research Office, the Department of Energy and the W.M. Keck Foundation.

9:00 AM *FF4.2
A Synthetic Molecular Motor Built from DNA. Jonathan Nicholas Bath, Physics, Oxford University, Oxford, United Kingdom.

We aim to construct a synthetic molecular motor that couples catalysis of a chemical fuel to directed movement along a linear track. The advantage of DNA as a material with which to build such a motor is that the strength and specificity of interactions between the component parts can be controlled by careful design of nucleotide sequences. The energy released by hydrolysis of the DNA backbone or hybridization of two DNA strands allows DNA to be used as both construction material and fuel. By designing the chemomechanical cycle of motor / fuel / track interactions we have engineered a strong directional bias and created a motor that can operate continuously while its fuel supply lasts.

9:30 AM *FF4.3
Programming Biomolecular Self-Assembly Pathways. Peng Yin[1,2], Harry Choi[1], Colby Calvert[1] and Niles Pierce[3,1]; [1]Bioengineering, Caltech, Pasadena, California; [2]Computer Science, Caltech, Pasadena, California; [3]Applied & Computational Mathematics, Caltech, Pasadena, California.

Molecular self-assembly, a fundamental process underlying the replication and regulation of biological systems, has emerged as an important engineering paradigm for nanotechnology, yet it remains challenging to mimic nature's ability to encode dynamic function in the design space of biomolecules. Here, we program diverse molecular self-assembly (and disassembly) pathways using a reaction graph abstraction to rewire complementarity relationships between modular domains in a versatile DNA hairpin motif. Molecular programs are executed for a variety of dynamic functions.

10:30 AM *FF4.4
Three Approaches to Assembling Micro Actuators using Molecular Motors. Yuichi Hiratsuka[1], Takashi Kamei[2] and Taro Q. P. Uyeda[2]; [1]School

of Materials Science, Japan Advanced Institute of Science and Technology (JAIST), Nomi, Ishikawa, Japan; [2]Research Institute for Cell Engineering, National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki, Japan.

Efforts to use protein molecular motors as nanoactuators are making rapid progress. For instance, it is now possible to carry out directional transport of small cargo along micro tracks or micro channels using the kinesin-microtubule motor system, which would be the basis of micro conveyor belts or molecular shuttles (reviewed by Hess and Vogel, 2001; Hiratsuka et al., 2006). However, the applicability of protein-based devices is limited by their poor stability in artificial environments. In addition, assembly of complex, intelligent microdevices or systems will likely require bottom-up self-assembly, but we still do not have sufficient knowledge to rationally design artificial self-assembling protein-based microdevices or systems. One approach to solving the problems associated with protein-based systems is to use DNA-based nanodevices, which are amenable to rational design. Indeed, ingenious design has enabled realization of DNA-based self-assembled two-dimensional micropatterns (Rothemund, 2006) as well as nanosized octahedrons (Shih et al., 2004). Prototypes of DNA-based molecular actuators have also been developed (e. g., Yurke et al., 2000). However, operation of these machines requires sequential addition of "fuel" oligonucleotides or enzymes. To realize more practical DNA-based molecular actuators, regulation of duplex formation of oligonucleotides by light is a promising approach. Thus, we are incorporating two photochromic molecules with different spectral properties into oligonucleotides, with the goal of realizing site-specific regulation of duplex formation. One could also use cells, organelles or tissues as preassembled motile units that move by the action of molecular motors inside them. Using this approach several motile devices have already been realized, including walking devices (Xi et al., 2005) and microfluidic pumps (Morishima et al., 2006) both driven by cardiac cells, and microtransporters that swim toward light (Weibel et al., 2005). We have been using the gliding bacterium Mycoplasma mobile, and established methods to direct the bacterial movement along linear tracks (Hiratsuka et al., 2005). More recently, we fabricated silicon dioxide micro rotors by conventional photolithography, and attached them to Mycoplasma cells circling in one direction within circular tracks (13 μm in diameter) through the biotin-avidin linkage. This resulted in rotation of the rotors at 2 rpm, which was the first bacteria-driven micro motor (Hiratsuka et al., 2006). However, the movement was terminated when the rotor was somehow detached from the track. To solve this problem for more stable rotation, we are currently fabricating micro rotors with more sophisticated design using two-photon microstereolithography. These protein-based, DNA-based, and cell-based systems each have distinct advantages and disadvantages, so that hybrid devices combining the best characteristics of all three would seem the most likely to succeed.

11:00 AM *FF4.5

Kinesin Motors at Work: From Cellular Function to Nanotechnological Applications. Stefan Diez, MPI-CBG Dresden, Dresden, Germany.

Inside cells, motor proteins perform a variety of complex tasks such as the transport of vesicles and the separation of chromosomes. We are interested in the novel use of such biological machines as transporters and manipulators for a wide range of nanoobjects in an engineered, cell-free environment. This idea is intriguing because such machines are robust, can work in parallel, their size is in the nanometer range, they work with a high energy efficiency and their application is potentially cheap. However, it is a major challenge to gain precise spatio-temporal control over the activity of the motor proteins when implemented in an artificial (cell-free) environment. One promising strategy to use the force generation of motor proteins in vitro is the so called gliding motility assay, where motor proteins (such as kinesin) are immobilized to the substrate and propel cytoskeletal filaments (such as microtubules) over the surface in the presence of ATP. In order to guide microtubules along predefined paths, we work on the generation of nanometer-wide, non-topographical patterns of motor proteins on planar surfaces (1). Towards the temporal control over motor activity by external signals, we fabricate composite surface layers where functional motor-molecules are adsorbed onto a silicon substrate between surface-grafted stimuli-responsive polymers (2). In order to observe and optimize the biologically driven transport processes in the nanometer range, it is a second goal to develop optical single molecule techniques. This includes imaging of single fluorescently labelled proteins (such as biomolecular motors) and colloidal semiconductor nanocrystals by total-internal reflection fluorescence (TIRF) and fluorescence interference contrast (FLIC) microscopy. These experiments shed light on the molecular conformation of kinesin motors during active transport (3), the cooperative behaviour of multiple kinesin-motors involved in cargo transport (4) and the detailed path of motor molecules on the microtubule (5).
(1) C. Reuther, L. Hajdo, R.Tucker, A.A. Kasprzak, S. Diez: Biotemplated nanopatterning of planar surfaces with molecular motors. Nano Letters, Vol. 6, 2177-2183, 2006 (2) L. Ionov, M. Stamm, S. Diez: Reversible switching of microtubule motility using thermosresponsive polymer surfaces. Nano Letters, Vol. 6, 1982-1987, 2006 (3) J. Kerssemakers, J. Howard, H. Hess, S. Diez: The distance that kinesin holds its cargo away from the microtubule surface measured by fluorescence-interference-contrast microscopy. PNAS, Vol. 103, no. 43, pp. 15812-15817, 2006 (4) C. Leduc, F. Ruhnow, J. Howard, S. Diez: Detection of fractional steps in cargo movement by the collective operation of kinesin-1 motors. PNAS, Vol. 104, no. 26, pp. 10847-10852, 2007 (5) J. Helenius, G. Brouhard, Y. Kalaidzidis, S. Diez, J. Howard: The depolymerizing kinesin MCAK uses 1D-diffusion to rapidly target the ends of microtubules. Nature, vol. 441, 115-119, 2006

11:30 AM *FF4.6

Biomolecular Motor-driven Assembly of Non-equilibrium, Nanocomposite Structures. George D. Bachand[1,2], Haiqing Liu[1], Erik Spoerke[3], Steven Koch[4], Bruce Bunker[3,2] and Marlene Bachand[1]; [1]Biomolecular Interfaces and Systems, Sandia National Laboratories, Albuquerque, New Mexico; [2]Center for Intergrated Nanotechnologies, Sandia National Laboratories, Albuquerque, New Mexico; [3]Electronic and Nanostructured Materials, Sandia National Laboratories, Albuquerque, New Mexico; [4]Department of Physics and Astronomy, University of New Mexcio, Albuquerque, New Mexico.

Biological systems exploit the interaction of energy-dissipating and thermodynamic processes to assemble nanostructures that are capable of responding (e.g., disassembling, reorganizing, and reassembling) to physiological signals or external stimuli. Exchanges of energy, matter, or entropy in such systems drive the assembly of complex structures that are highly non-equilibrium. We have recently demonstrated the ability of kinesin motor proteins to dynamically assemble and disassembly nanocomposite structures consisting of microtubules and semiconductor nanocrystals. Three distinct phases of the composites were generated by systematically varying the conditions of assembly: (1) mobile linear composites, (2) rotating circular composites, and (3) immobile aggregates. The formation of these different phases is highly dependent upon the interaction of energy-dissipating (i.e., motor protein-based transport) and thermodynamic (i.e., non-covalent bond formation) processes. In particular, the circular composites are assembled through a nonlinear cyclic process. The balanced interaction of energy-dissipative and thermodynamic forces results in the formation of metastable "nano-springs" that are mechanically constrained and capable of storing ~135 aJ of elastic energy. A key feature driving the assembly of these composites involves the hierarchical amplification of microtubule rotation into the rotating composite structures. This presentation will describe how energy-dissipative processes, thermodynamics, and microtubule mechanics interact to drive the assembly and disassembly of these unique composite structures. *Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, or the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

SESSION FF5: Fundemental Mechanisns Of Nanoscale Motion
Chair: Heiner Linke
Wednesday Afternoon, March 26, 2008
Room 3018 (Moscone West)

2:00 PM *FF5.1
Trapping and Manipulating Single Molecules in Solution. Adam Cohen, Chemistry and Physics, Harvard University, Cambridge, Massachusetts.

The Anti-Brownian Electrokinetic trap (ABEL trap) is a device that allows a user to trap and manipulate individual fluorescent molecules in solution. The ABEL trap uses real-time tracking coupled with electrokinetic feedback to impose forces on a single molecule that are timed and oriented to cancel its translational Brownian motion. A new design for the ABEL trap will be presented in which the tracking is implemented with temporal and spatial resolution limited by shot-noise and diffraction, respectively. This new device is capable of trapping smaller particles than have been trapped by other means. Examples of studies of free-solution dynamics of a variety of biomolecules will be presented.

2:30 PM *FF5.2
Statistical Mechanics of Small Systems. Christian Van den Broeck, Hasselt University, Diepenbeek, Belgium.

We review recent progress in the statistical mechanics of small systems, including Maxwell demons, Brownian motors, Brownian refrigerators, fluctuation theorem and work theorem. We also present a new approach to deal with the second law of thermodynamics and its relation to the thermodynamics of computation. C. Van den Broeck, P. Meurs and R. Kawai, " From Maxwell Demon to Brownian Motor", New J. Phys. 7, 10, 1-23 (2005). C. Van den Broeck, " Thermodynamic Efficiency at Maximum Power", Phys. Rev. Lett. 95, 190602, 1-3 (2005). C. Van den Broeck and R. Kawai, “Brownian Refrigerator”, Phys. Rev. Lett. 96, 210601, 1-4 (2006). C. Van den Broeck, “ Carnot Efficiency Revisited”, Adv. Chem. Phys. 135, 189-201 (2007). R. Kawai, JMR. Parrondo and C. Van den Broeck, "Dissipation: the Phase-Space Perspective", Phys Rev Lett 98, 080602 (2007)

3:30 PM *FF5.3
Preparing a Mechanical Resonator into the Quantum Ground State. Keith Schwab, Physics, Cornell University, Ithaca, New York.

We pursuing experiments to both prepare and measure mechanical structures into the quantum ground state. I will review our recent results with nano-electro-mechanical structures at ultra-low temperatures measured with precision near the Heisenberg Uncertainty Principle Limit and cooled to quantum state $<N>=25$. I will also give an update on our recent work to cool to the quantum ground state by parametrically coupling a nanomechanical resonator to a superconducting microwave resonator.

4:00 PM FF5.4
Micromachined Linear Brownian Motor: A Nanosystem Exploting Brownian Motion of Nanobeads for Uni-directional Transport. Ersin Altintas[1], Edin Sarajlic[1], Karl F. Bohringer[2] and Hiroyuki Fujita[1]; [1]Electrical Engineering, CIRMM/IIS, The University of Tokyo, Tokyo, Japan; [2]Electrical Engineering, The University of Washington, Seattle, WA, Washington.

Nanosystems operating in liquid media may suffer from Brownian motion. Known natural nanosystems such as biomolecular motors utilize rather than fight Brownian motion. Here, we present a bio-inspired, micromachined Brownian motor to exploit Brownian motion of 500 nm nanobeads to fuel their uni-directional transport. Characterization of the performance shows that the average speed of the motor is dependent on the switching sequence of the phases, and peaking around the expected diffusion time of the particles between electrodes. The Micromachined Linear Brownian Motor (LBM) employs microchannels to limit the 3D random motion of nanobeads into 1D (taming), and equally spaced 3-phase electrodes for the rectification of the motion for unidirectional transport (Fig. 1). Unlike in an electrostatic motor, Brownian motion provides the motive force; however, during the ON state, a periodically cycling 3-phase electrostatic field immobilizes beads coming on active electrode to produce a net displacement. In the OFF state, the particle diffuses; the system works as a flashing ratchet mechanism. The rectification increases the probability in the cycling direction. Recently, we devised the first LBM and demonstrated its working principle. Our device (Fig. 2) consists of a cover glass with ITO electrodes fabricated by a lift-off process. A PDMS sheet with 1 μm deep and 2 μm wide channels is aligned and bonded on the cover glass. A fixed driving voltage of 0.5Vpp-1MHz is employed. Under these conditions, buoyancy forces and electro-hydro-dynamical forces are negligible. Fig. 3 shows the trace of the rectification of the Brownian motion of nanobeads over electrodes. We have experimentally characterized transportation performance of the motor for electrode spacing, excitation time te (ON-State), and Brownian time of particles tb (OFF-State). Figure 4 shows the effect of electrode spacing (LBM-2 2μm spacing, LBM-4 4μm spacing) and excitation time te. LBM-2 has larger displacements (final position-initial position) due to small spacing between electrodes for the beads to diffuse. At longer rectification time, te, it is more probable for beads to reach the electrodes by diffusion and to be trapped by the field; therefore, the displacement would be larger. To investigate the effect of tb, te was kept as 4 seconds. tb improves the performance of the system (Fig. 5). Comparison of tb = 0, 4 and 8 seconds reveals that displacements are strongly dependent on Brownian motion. However, if we look at the average speed of the beads (Fig. 6) over total experiment time (5×3×(te+tb)), it is te dependent and it peaks near a time, tb*=<(Electrode spacing)^2>/2D, the theoretically expected time necessary for a particle diffusing from one electrode to the another. Increasing tb further would not improve the average speed of the motor. This work aims at an engineering solution to novel and efficient nanosystems exploiting Brownian motion inspired by biomolecular motors.

4:15 PM FF5.5
Interplay between Current Reversal and Collective Particles Behaviour in Ratchet Devices. Luis Dinis[2], Elvira M. Gonzalez[1], Juan M. R. Parrondo[2] and Jose L. Vicent[1]; [1]Fisica Materiales, Univ. Complutense, Madrid, Madrid, Spain; [2]Fisica Atomica Nuclear y Molecular, Univ. Complutense, Madrid, Madrid, Spain.

We have modelled the ratchet behaviour of interacting and overdamped Brownian 2D particles moving on arrays of asymmetric potentials. We have studied the effect on the current reversal of the asymmetric potential strength, the number of particles per array unit cell and the external force values. We have found that ratchet current reversal could be induced by: i) Reconfiguration of the particle lattice. ii) Instability of the ground state of the particles lattice. This model has been tested using as particle lattice a superconducting vortex lattice and as asymmetric potential wells asymmetric nanodefects embedded in superconducting films. The experimental results show that current ratchet reversal, induced by the aforementioned mechanisms, is a robust effect that could be measured at temperatures close to the superconducting critical temperatures. At constant temperature this reversal current could vanish modifying the potential strength or the number of particles.

4:30 PM *FF5.6
Self Excitation in Nanomechanical Systems. Robert H Blick, Electrical and Computer Engineering, University of Wisconsin-Madison, Madison, Wisconsin.

This talk will give an overview of mechanically mediated electron transport in nano-electromechanical systems (NEMS). One aspect will cover self excitation in NEMS: self excitation is a mechanism which is ubiquitous for electromechanical power devices such as electrical generators. This is conventionally achieved by making use of the magnetic field component in electrical generators, where a good example is the overall visible wind farm turbines. In other words, a static force, like wind acting on the rotor blades, can generate a resonant excitation at a certain mechanical frequency. For nanomechanical systems such a self excitation (SE) mechanism is highly desirable as well, since it can generate mechanical oscillations at radio frequencies by simply applying a DC bias voltage. This is of great importance for low-power signal communication devices and detectors, as well as for mechanical computing elements. We use a nano-electromechanical single electron transistor (NEMSET) to demonstrate self excitation for both the soft and hard regime, respectively. The ability to use self excitation in nanomechanical systems may enable the detection of quantum mechanical backaction effects in direct tunneling, macroscopic quantum tunneling, and rectification.